PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter II of the Patent Cooperation Treaty)

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference PCT25654	**FOR FURTHER ACTION**	See Form PCT/IPEA/416
International application No. PCT/IT2004/000380	International filing date *(day/month/year)* 09.07.2004	Priority date *(day/month/year)* 13.08.2003
International Patent Classification (IPC) or national classification and IPC G03H1/08		
Applicant CONSIGLIO NAZIONALE DELLE RICERCHE et al		

1. This report is the international preliminary examination report, established by this International Preliminary Examining Authority under Article 35 and transmitted to the applicant according to Article 36.
2. This REPORT consists of a total of 7 sheets, including this cover sheet.
3. This report is also accompanied by ANNEXES, comprising:
   a. ☒ *sent to the applicant and to the International Bureau)* a total of 18 sheets, as follows:
      - ☒ sheets of the description, claims and/or drawings which have been amended and are the basis of this report and/or sheets containing rectifications authorized by this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions).
      - ☐ sheets which supersede earlier sheets, but which this Authority considers contain an amendment that goes beyond the disclosure in the international application as filed, as indicated in item 4 of Box No. I and the Supplemental Box.

   b. ☐ *(sent to the International Bureau only)* a total of (indicate type and number of electronic carrier(s)) , containing a sequence listing and/or tables related thereto, in computer readable form only, as indicated in the Supplemental Box Relating to Sequence Listing (see Section 802 of the Administrative Instructions).

4. This report contains indications relating to the following items:

☒	Box No. I	Basis of the opinion
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☒	Box No. VII	Certain defects in the international application
☒	Box No. VIII	Certain observations on the international application

Date of submission of the demand 05.05.2005	Date of completion of this report 05.12.2005
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized Officer Noirard, P Telephone No. +49 89 2399-2420

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

International application No.
PCT/IT2004/000380

Box No. I Basis of the report

1. With regard to the **language**, this report is based on the international application in the language in which it was filed, unless otherwise indicated under this item.

   ☐ This report is based on translations from the original language into the following language , which is the language of a translation furnished for the purposes of:
   - ☐ international search (under Rules 12.3 and 23.1(b))
   - ☐ publication of the international application (under Rule 12.4)
   - ☐ international preliminary examination (under Rules 55.2 and/or 55.3)

2. With regard to the **elements*** of the international application, this report is based on *(replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report)*:

Description, Pages

1-15	received on 01.07.2005 with letter of 04.05.2005

Claims, Numbers

1-14	received on 01.07.2005 with letter of 04.05.2005

Drawings, Sheets

1/5-4/5	as originally filed
5/5	received on 01.07.2005 with letter of 04.05.2005

☐ a sequence listing and/or any related table(s) - see Supplemental Box Relating to Sequence Listing

3. ☐ The amendments have resulted in the cancellation of:
   - ☐ the description, pages
   - ☐ the claims, Nos.
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

4. ☒ This report has been established as if (some of) the amendments annexed to this report and listed below had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).
   - ☐ the description, pages
   - ☒ the claims, Nos. 11
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

* *If item 4 applies, some or all of these sheets may be marked "superseded."*

Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-10,12-13
	No:	Claims	
Inventive step (IS)	Yes:	Claims	1-10,12,13
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-10,12,13
	No:	Claims	

2. Citations and explanations (Rule 70.7):

see separate sheet

Box No. VII Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

Box No. VIII Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:

see separate sheet

Re Item I
Basis of the report

1.1 The amendments filed with the letter dated 04/05/05 introduce subject-matter which extends beyond the content of the application as filed, contrary to Article 34(2)(b) PCT. The unallowable amendments concern the newly added claim 11.
Indeed, it has not been found in the original description, that the method may be performed for "more than one holographic images detected at the same time" and subsequently "superposed".
Although the reasoning given is the letter of reply (page 3) is considered to be correct, the cited passages in the description (in particular page 3, lines 30-33) do not allow the skilled person to implicitly consider simultaneous (alternativelly, a frame sequential acquisition with a single CCD and a coloured wheel may also be used) and multiple (alternatively, a trichrome single "image" recorded with a RGB CCD may also be envisaged) acquisitions.
In addition, the wording of the claim is confusing since the method starts from "holographic images" to obtain "holographic image" (obtaining the "reconstructed image" defined in claim 1, would solve the problem).

1.2 However, from the cited passages, colour digital holography may be allowed (e.g. the method may be respectively performed for different wavelengths components of a coloured holographic image to obtain a multi-colour final reconstructed object).

Re Item V
Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

2. Reference is made to the following documents:
D1: KREIS T M ET AL: "METHODS OF DIGITAL HOLOGRAPHY: A COMPARISON" PROCEEDINGS OF THE SPIE, SPIE, BELLINGHAM, VA, US, vol. 3098, 1997, pages 224-233, XP000964987 ISSN: 0277-786X
D2: BERNHARDT M ET AL: "CODING AND BINARIZATION IN DIGITAL FRESNEL HOLOGRAPHY" OPTICS COMMUNICATIONS, NORTH-HOLLAND PUBLISHING

CO. AMSTERDAM, NL, vol. 77, no. 1, 1 June 1990 (1990-06-01), pages 4-8, XP000127687 ISSN: 0030-4018

3.1 The document D1 is regarded as being the closest prior art to the subject-matter of the claims, and shows (the references in parentheses applying to this document): a method for reconstructing holographic images (cf. abstract) wherein a digitized hologram is detected and digitized by an image detection device (cf. paragraph 2 and Fig. 1c), thereby generating an array having Vr pixels (see Fig. 2) whose sizes are given by the sampling interval of the image detection device (cf. paragraph 2). This array is further processed and a discrete Fresnel transform is applied on it to reconstruct the object (cf. paragraph 3).

3.2 D1 fails to teach
* firstly, that, prior to apply the Fresnel transform, the digitized hologram is embedded into an array having Ve values, wherein Ve is larger than Vr; and,
* secondly, that Ve is inversely proportional to the desired pixel size to be obtained for the reconstructed object.

3.3 The subject-matter of claim 1 is therefore new (Article 33(2) PCT).

3.4 The problem to be solved by the present invention may be regarded as providing a method of reconstructing a digital hologram allowing a better reconstructed resolution and a scaling effect.

3.5 The solution to this problem proposed in claim 1 of the present application is considered as involving an inventive step (Article 33(3) PCT) for the following reasons:

3.6 One the one hand, although D1 teaches in §4 to embed the digitized hologram into a larger zero matrix (see also Figs. 5,6) in order to perform a scaling function, the corresponding disclosed method is applied to digital holograms processed through the convolution approach, which convolution approach (detailed §4 in D1) is an mutually exclusive alternative to the Fresnel-approximation method (detailed §3 in D1). Furthermore, D1 makes it clear that both methods are different, in particular with respect to the sizes of the "reconstruction pixels" building the "resulting image" (see abstract,

and equations 9,16 in D1) and also stresses that the Fresnel approach leads to sizes dependency of the reconstructed objects (see abstract in D1). Therefore, it is considered that this teaching disclosed in D1 in the context of the convolution approach cannot obviously be applied/transferred to the Fresnel transform approach.

3.7 One the other hand, D2 teaches to generate holograms using the Fresnel-approximation method (cf. §2 in D2) and teaches to encloses the target matrix into a larger zero array in order to separate the reconstructed image from the noisy first order (see Fig. 1a, 1b in D2). Since D2 generate a hologram from a target image whereas the present application reconstruct an object from a hologram, the scaling objective problem addressed in the present claim is not applicable to D2 and the skilled person would have no motivation to derive from D2 that the size of the larger matrix should be inversely proportional to the desired pixel size to be obtained for the reconstructed object.

4. Claims 2-10 and 12-14 are dependent on claim 1 and as such also meet the requirements of the PCT with respect to novelty and inventive step.

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5. The industrial applicability (Article 33(4) PCT) is clearly present for the subject matter of all the claims.

Re Item VII
Certain defects in the international application

6. In the original description, the following points should be checked
   * page 2, lines 6,7, M and N are inverted;
   * page 8, line 14, and instead of ad;
   * page 10, line 21, in the equation, left hand side :delta ksi et delta eta, right hand side, indexes m,n instead of l,k.

Re Item VIII
Certain observations on the international application

7. Claim 1 does not meet the requirement of Article 6 PCT in that the subject matter for which protection is sought lacks clarity because the expression "equal to OS" refers to an unknown value "OS" which may be interpreted as 0s (zeros). Correspondingly, in claim 2 the expression in bracket may be cancelled.

10/566036

IAP20 Rec'd PCT/PTO 25 JAN 2006

METHOD FOR MODIFYING SPATIAL RESOLUTION IN THE RECONSTRUCTION OF IMAGES IN DIGITAL HOLOGRAPHY

The present invention refers to a method for modifying spatial resolution in the reconstruction of images in digital holography.

More particularly, the method according to the present invention allows the process of reconstruction of images employed in the interferometric technique of digital holography to be improved, thanks to the improvement of the spatial resolution of the reconstructed complex field, which allows upgrading applications of Digital Holography technique.

The interferometric technique, allowing recording and reconstructing the complex (amplitude and phase) field reflected, transmitted and/or scattered by an object, is commonly called in scientific literature as Digital Holography, which will be hereinafter abbreviated with the acronym DH (e.g. see: US Patent No. 6,262,818, to Cuche et al., entitled "Method for simultaneous amplitude and quantitative phase contrast imaging by numerical reconstruction of digital holograms", and US Patent No. 6,246,495, to Yamaguchi, entitled "Phase-shift digital holographic apparatus").

It is called digital hologram an interference pattern recorded by means of an integrated array of radiation detectors.

Several methods exist allowing the numerical reconstruction of the complex field starting from the hologram, and in particular there are the "convolution" method and the one called the "Fresnel" method.

In particular, in Fresnel method, as it is known, the spatial resolution of the complex field (or also amplitude and phase) is determined by some parameters. Some of these parameters are determined by the characteristics of the integrated array of radiation detectors and, in particular, by the number of elements of which the array is composed and by the size of the single element. Besides, other parameters are the reconstruction distance, determined by distance d at which the object (or points of its surface and its volume), and the wavelength λ of the light source, used for creating the hologram, which are employed in the numerical process of reconstruction.

Commonly, in literature, the spatial resolution is quantified by means of the "reconstruction pixel", which is expressed as a length, and which will be hereinafter indicated with the acronym PR. The dimensions

of the bidimensional PR, $\Delta\xi$ along the x-axis and $\Delta\eta$ along the y-axis, depend on the aforementioned parameters through the following mathematic formulas:

$$\Delta\xi = \frac{\lambda d}{N\,\Delta x} \qquad \Delta\eta = \frac{\lambda d}{M\,\Delta y} \qquad (1)$$

where M is the number of acquired pixels (acquired by an image acquisition device) along the x-axis, N is the number of pixels along the y-axis, Δx and Δy are the pixel size along the two directions of x- and y-axis.

From this formula, it is clear that the complex field will have a PR of different value at different distances, keeping constant the other parameters, and in particular the size of PR increases under the increase of the reconstruction distance. In such case, the spatial resolution with which the complex field is reconstructed will have an inferior spatial resolution. On the contrary, the spatial resolution will be superior at lower reconstruction distance since in this case the PR size decreases.

In other applications, as for example spectroscopic or scattering enquiries, it is required the recording of several holograms of the same object under the same conditions, but obtained with different source wavelengths (or with different sources at different wavelengths) (e.g. see the paper by M.K. Kim, "Wavelenght-scanning digital interference holography for optical section imaging", *Optics Letters*, Vol. 24, Issue 23, 1999, page 1693). In such case, by applying the reconstruction process to the several holograms related to each wavelength, holograms will be obtained which are reconstructed with different spatial resolutions, since, as it appears clear from equation (1), the PR for each wavelength is different. In particular, the reconstruction resolution will be higher for lower wavelengths which give lower PR values and vice versa.

In the state of the art prior to the present invention, there exist some problems connected to the fact that the reconstruction resolution is rigidly determined by some parameters such as distance and wavelength. By way of example, some particularly problematic cases will be mentioned in the following.

In some applications, digital holography is used for analysing variations to which the object under observation is subject because of an external action (e.g. force, pressure, temperature change). The variations are measured in a quantitative way by subtracting the phase maps of two

holograms recorded with the object in two different states (for example before and after the external disturbance action). This technique is called Digital Holographic Interferometry.

In these dynamic type observations, the distance between the object under observation and the detection device (e.g. a camera), at which the hologram is recorded, could unintentionally change, obtaining different holograms recorded with the object placed at different distances from the detection device. Hence, in order to observe the object always in focus, it is necessary to change the value of distance to be employed in the reconstruction process (see the paper by Ferraro *et al.* in *Optics Letters*, 28(14), (2003), 1257-1259) for each recorded hologram.

From equations (1), it results that the PR value is different for holograms reconstructed at different distances, and the spatial resolution, with which the object (in the complex field: amplitude and phase) is reconstructed in the various holograms, is consequently different. This avoids carrying out in a direct way a difference of phase obtained, for instance, with two holograms separately reconstructed at two different distances, by actually preventing digital holographic interferometry technique from being applied. In fact, since reconstruction resolution is different in the two holograms, it is then not possible to carry out a direct subtraction of the phase maps (a one-to-one correspondence among the points of the two maps does not exist).

In general, the change of either the wavelength or the distance between object and camera, may make the resolution with which it is possible to observe the object worst.

This generally prevents any direct subtraction of phase between the two reconstructed images for detecting and quantifying small physical-mechanical variations of the object. Such subtraction procedure is typically employed in the "holographic interferometry" technique allowing different states of the same object to be compared.

Similarly, in case of applications of colour DH with use of different wavelengths, images reconstructed with different wavelengths do not overlap since the PR of each reconstruction is different (e.g. see the paper by I.Yamaguchi, "Phaseshifting color digital holography", *Optics Letters*, Vol. 27, Issue 13, July 2002, page 1108, and the paper by J.Kato et al., "Multicolor digital holography with an achromatic phase shifter", *Optics Letters*, Vol. 27, Issue 16, 2002, page 1403.

M. Bernhardt *et al.* in the article "Coding and binarisation in digital Fresnel holography", *Optics Communications*, North-Holland Publishing Co. Amsterdam, vol.77 no.1, 1June 1990, p.4-8, deals with the use of Fresnel Transform in the reconstruction of images in DH (improving diffraction efficiency).

T. M. Kreis *et al.* in the article "Methods of Digital Holography: a comparison", *Proceedings of the SPIE*, SPIE, Bellingham, VA, US, vol.3098, 1997, pages 224-233, ISSN: 0277-786X, teaches to embed a digitised hologram into an array having a larger number of pixels in the specific context of the convolution approach, in order to vary the size of the reconstructed images.

In the latter article, moreover, it is concluded that the Fresnel approach cannot be applied if reconstruction in different depths are to be compared, and inversely, the convolution approach is not much suited if the whole possible field of view for opaque or transparent objects has to be reconstructed.

A general method of varying the resolution of the reconstructed image is not provided in the prior art.

The Applicant does not know effective solutions to the above problems.

In fact, as it results from literature, the methods presently employed for obtaining a better resolution in observation of objects make use of complex experimental apparatuses requiring particularly delicate calibration procedures (e.g. see: Indebetouw *et al.*, *Appl. Phys. Lett.* 75, (1999) 2017-2019).

It is an object of the present invention to provide a method of reconstruction of the holographic image starting from a digitized hologram solving the above drawbacks and enabling further uses.

It is also an object of the present invention to provide apparatuses and tools necessary for the execution of the method that is object of the invention.

It is further object of the present invention an apparatus for acquiring and reconstructing holographic images making use of the method that is object of the invention.

It is specific subject matter of this invention a method for the reconstruction of holographic images, the holographic image being detected by an image detection device, the holographic image being

transformed in a digitized hologram, the digitized hologram being comprised of a number V_r of elementary pixels, the size of which being equal to the holographic image sampling intervals, and of the V_r values respectively associated to the elementary pixels, the method comprising a first step of processing the digitized hologram array, and a second step of hologram reconstruction in the observation plane starting from the digitized hologram processed in the first step, the method being characterised in that the second step is carried out through discrete Fresnel Transform applied on an array of V_e values corresponding to pixels having size equal to that of said elementary pixels, wherein said array of V_e values) includes said array of V_r values and an integer number $p = V_e - V_r > 0$ of constant values equal to OS, said number V_e of values being inversely proportional to the desired pixel size to be obtained for the reconstructed image.

Preferably according to the invention, said p constant values are null values ($OS = 0$).

Still preferably according to the invention, said p values are arranged externally to said array of V_r values.

Always according to the invention, said p values may be arranged in a symmetrical way or in a non-symmetrical way.

Preferably according to the invention, the digitized hologram is a rectangular array of $V_r = N_r \cdot M_r$ values, each value corresponding to a rectangular pixel of sizes Δx, Δy.

Still preferably according to the invention, the hologram reconstructed in the second step is represented by a rectangular array of $V_e = N_e \cdot M_e$ values, each value corresponding to a rectangular pixel of sizes $\Delta\xi = (\lambda d / N_e \Delta x)$ and $\Delta\eta = (\lambda d / M_e \Delta y)$, λ being the wavelength of the wave beam striking the object of which the hologram is recorded, and d the distance between the detection device and the object of which the hologram is detected, $\Delta\xi$ and $\Delta\eta$ being the reconstructed holographic image sampling intervals.

According to the invention, formulas $N_e = (\lambda d / \Delta x^2)$, $M_e = (\lambda d / \Delta y^2)$, $\Delta\xi = \Delta x$, $\Delta\eta = \Delta y$ may be valid.

Advantageously according to the invention, after the second step, if each holographic image sampling interval is not equal or less than a certain threshold, the number of values p added to the digitized hologram array is increased and the second step is carried out again.

Preferably according to the invention, said threshold is a function of the signal-to-noise ratio of the holographic image.

According to the invention, the method can be performed for more than one holographic images detected at the same time for different wavelength λ, said more than one images being subsequently superposed in order to obtain a multi-colour final holographic image.

It is further specific subject matter of the present invention a computer program characterised in that it comprises code means apt to execute, when running on a computer, the method subject of the invention.

It is still specific subject matter of the invention a memory medium, readable by a computer, storing a program, characterised in that the program is the computer program subject of the invention.

It is further specific subject matter of the invention an apparatus for detection of holographic images, comprising a digitized hologram processing unit, characterised in that the processing unit processes the detected data by using the method subject of the invention.

The invention will be now described, by way of illustration and not by way of limitation, by particularly referring to the drawings of the enclosed Figures, in which:

- figure 1 shows a block and flow hybrid diagram of the traditional holographic reconstruction method;

- figure 2 shows a block and flow hybrid diagram describing the holographic reconstruction method according to the invention;

- figure 3a shows the effect of the reconstruction in amplitude of a Talbot effect Ronchi grating made through the traditional method;

- figure 3b shows the effect of the reconstruction in amplitude of a Talbot effect Ronchi grating made through the method according to the invention;

- figure 4a shows a particular information related to the reconstruction of figure 3a, in relation to a certain reconstruction distance, as a function of the number of pixels;

- figure 4b shows a particular information related to the reconstruction of figure 3b, in relation to a certain reconstruction distance, as a function of the number of pixels; and

- figure 5 shows a preferred arrangement of the null pixels used in the method according to the invention.

As mentioned before, digital holography consists of recording a distribution of interference, which is created between an object beam (that has interacted with the object under observation) and a reference beam, through an ad hoc system for acquiring images.

Such interference distribution is processed through processing methods apt to reconstruct an image of the object under observation.

In particular, the recorded hologram is multiplied by a digital replica of the reference beam and the diffraction integral of this product is calculated. Such hologram allows a reconstruction of the object under observation to be obtained.

The reflection holographic recording apparatus may be for instance of the Mach-Zehnder type. Once analogue data are acquired, they are processed by a processing unit.

Making reference to figure 1, such processing unit processes data according the traditional method. The unit of preparation of hologram acquisition conditions or "set-up" 2 collects radiation 4 coming from source 1 and illuminate with radiation 5 the object 3 under observation. Also, in such set-up 2 is present a device for creating, from the beam 6 that is reflected, transmitted or scattered by the object 3, an object beam O, and a device for creating a reference beam R. The object beam O and the reference beam R are combined in the set-up 2 so as to create an interference distribution 7 in a plane. Such interference creates the hologram 8 of the object 3 under observation, and it may be described in terms of bidimensional distribution of intensity:

$$H(x,y)=|R|^2+|O|^2+R^*O+RO^*$$

where $R*$ and $O*$ represent the conjugate complex of the reference beam and of the object beam, respectively.

It is now necessary to specify that, as it will be shown later, the method according to the present invention is not restricted to the optical field and it may be applied for the numerical reconstruction of holograms recorded with any type of electromagnetic (for instance X rays) and non-electromagnetic radiation (for instance electron beams and/or acoustic waves). In particular, source 1 could be also made of a combination of two or more wavelengths. For this reason, type, wavelength and coherence of source 1 could be any.

The hologram 8 is acquired, digitized and stored through an acquisition system 9. To this end, any type of existing or future image acquisition system may be used.

The acquisition system 9 internally has a device for digitizing and computer storing the acquired image 8. The digitized image is called "digital hologram" 10 and it is described by an array $H(n\cdot\Delta x, m\cdot\Delta y)$ of $N\cdot M$ numbers, obtained by the bidimensional spatial sampling of the hologram $H(x,y)$ 8.

Such bidimensional spatial sampling may be described by the following formula:

$$H(n\Delta x, m\Delta y) = H(x, y) rect\left(\frac{x}{N\Delta x}, \frac{y}{M\Delta y}\right)\sum_{n=1}^{N}\sum_{m=1}^{M}\delta(x - n\Delta x, y - m\Delta y)$$

where $\delta(x,y)$ is a bidimensional Dirac delta function, n and m are integer, Δx and Δy are the sampling spacings along the x-axis and the y-axis respectively, $(N\cdot\Delta x)\times(M\cdot\Delta y)$ is the area of the image of the acquired hologram, $rect(x,y)$ is a function the value of which is 1, if the point of coordinates (x,y) is within the part of the acquired hologram, and 0 otherwise.

For a perfect reconstruction of the object image, it is necessary that the digitization process satisfies the sampling theorem. In particular, it has to be satisfied the condition that the spacing between the fringes present in the interference distribution 7 is larger than at least two pixels of the acquisition system 9. Hence, the sampling theorem establishes the minimum resolution that is obtainable with a certain experimental set-up 2.

One of the great advantages offered by the digital holography is the fact that it is possible to directly act on the digitized hologram 10 of the object 3 for carrying out operations on the acquired information.

This means that different processings of the images 11 may be made on the digitized hologram 10. Through such processings, it is for example possible to eliminate zero order diffraction present in hologram reconstruction, or to eliminate any "phase aberration" introduced by the used optical system.

The term "phase aberration" means a deformation of the wave front travelling through the hologram creation ad recording system. The phase aberration correction compensates such deformations and allows obtaining a correct reconstruction of the observed object.

The process of numerical reconstruction 13 of the object under observation is based on two steps. In the first one, the "processed" digitized hologram $H(n,m)$ 12 has to be multiplied by a digitized replica of the reference beam R, obtaining the following formula:

$$F(n\Delta x, m\Delta y) = H\ (n\Delta x, m\Delta y) \cdot R(n\Delta x, m\Delta y) =$$
$$= R|R|^2 + R|O|^2 + RR^*O + RRO^*$$

where the first two terms correspond to the zero order diffraction, and from the third and/or fourth term it is possible to obtain the image of the observed object.

The second step of the propagation process consists of the propagation of the field distribution $F(n,m)$ from the plane wherein the camera is placed to the observation plane. This process leads to the reconstructed image 14.

It is then possible to numerically act on the recorded and stored digitized hologram through an electronic device for image acquisition (hereinafter generically called as camera) made of a discrete set of sensitive elements arranged in the shape of array of N rows and M columns, in order to obtain a higher spatial resolution with respect to the techniques presently in use.

In order to overcome the aforementioned drawbacks of the traditional method, the method according to the present invention is based on the extension of the array of the object hologram by introducing a number of additional fictitious points, the intensity of which is set to zero.

The object is then reconstructed with the technique of the hologram numerical propagation from the camera plane along the distance separating the object from the same plane of the camera.

The hologram propagation occurs by using the bidimensional Fresnel transform. The advantage of such integral is that its computation is simple and may be very fast performed by using a discrete formulation expressed in terms of Fourier transform. In fact, it is well known (see Goodman, "Introduction to Fourier Optics", MacGraw-Hill Companies Inc., 2nd ed., 1996) that the phenomenon of light propagation from a starting plane to a parallel plane placed at a distance *d* may be interpreted as a space-invariant linear system characterised by a transfer function having a finite band amplitude. Such transfer function has unitary module and phase depending on the spatial frequencies corresponding to the two

orthogonal directions within the plane placed at a distance z from the starting plane.

In case of propagation of an optic field through the Fresnel numerical integral, the transfer function phase quadratically depends on the spatial frequencies. Consequently, dispersive effects are introduced in the hologram numerical reconstruction process which increase with the increase of the reconstruction distance and which generally contribute to make the reconstructed hologram spatial resolution worst.

As it will be clarified in the following, the extension of the dimension of the hologram array, by adding null elements, allows acting on the size of the minimum element composing the object reconstructed image (the "reconstruction pixel"), rather improving its resolution.

Making reference to figure 2, as in the traditional case, for carrying out the method according to the invention it is first of all necessary to have a holographic system for creating a hologram of the object under observation.

Such hologram is digitized and computer stored through a camera. The digitized hologram is a rectangular array obtained by sampling the hologram by means of the camera with a step Δx along the x-axis and a step Δy along the y-axis (Δx and Δy coincide with the camera pixel size) for a number of points equal to $N{\cdot}M$ (N is the number of camera pixels along the x-axis and M is the number of camera pixels along the y-axis).

The array size related to the digitized hologram is then enlarged by adding a suitable number of points so as to obtain the desired resolution in the hologram reconstruction process.

By using such extended array, it is then possible to exploit the technique of the bidimensional Fresnel transform for reconstructing the image of the object under observation, so gaining in definition.

In the configuration preferred by the inventors, set-up 2 is designed so as to produce a "Fresnel hologram", term indicating a hologram that may be reconstructed through Fresnel scalar diffraction approximation.

The advantages of such approximation derives from the fact that its computation is very simple and may be performed in a very fast manner. In case of Fresnel approximation, numerical reconstruction of the hologram 12 will be carried out according to the invention through a

discrete formulation of the Fresnel integral expressed in terms of discrete Fourier transform, that is:

$$\psi(l\Delta x, k\Delta y) = Ae^{\frac{i\pi}{\lambda d}(l^2\Delta\xi^2 + k^2\Delta\eta^2)} DFT\left[R(n\Delta x, m\Delta y) H\,(n\Delta x, m\Delta y) e^{\frac{i\pi}{\lambda d}(n^2\Delta x^2 + m^2\Delta y^2)}\right]_{l,k}$$

where λ is the wavelength of source 1, A is a complex constant, n, m, l, k are integer ($-N/2 \le n,l \le N/2$ and $-M/2 \le m,k \le M/2$), DFT is the discrete Fourier transform, which may be fast computed by making use of multiple FFT (Fast Fourier Transform) algorithms reported in literature, Δx and Δy are the sampling spacings of the hologram 12 (hence in the camera plane), d is the distance between the camera plane and the observation plane, and, finally, $\Delta\xi$ and $\Delta\eta$ represent the sampling spatial intervals in the observation plane which are defined by:

$$\Delta\xi = \frac{\lambda d}{N\,\Delta x} \qquad \Delta\eta = \frac{\lambda d}{M\,\Delta y} \qquad (1)$$

Hence, the reconstructed object will have size $(N \cdot \Delta\xi) \times (M \cdot \Delta\eta)$. The intervals described by equations (1) substantially define the resolution of the reconstructed object 14.

As it may be noted from the preceding formula, the resolution also depends on, besides the number of pixels and the resolution of the acquisition system 9, the wavelength λ of the source 1 and the reconstruction distance d.

In the reconstruction processes, it is generally $\Delta\xi > \Delta x$ and $\Delta\eta > \Delta y$, i.e. the reconstructed object image is characterised by an inferior resolution with respect to the one with which the hologram 8 has been digitized and recorded.

As shown in the following, the method according to the invention allows solving the aforesaid problem and, keeping constant wavelength and reconstruction distance d, improving the resolution of the image of the reconstructed object 14.

Always making reference to figure 2, on the one hand, the proposed method allows the system of creation and recording of the hologram 8 not to be modified, and, on the other hand, it is compatible for applications wherein the hologram recording has to be carried out in real time and in a continuous way.

In the version presently preferred by the inventors, the method acts on the processed hologram 12, that is on the hologram which has

been already subject to processing for a correct reconstruction of the object 3.

The size of the array describing the digitized hologram 12 is expanded during step 15 by adding a certain number of points as determined in step 16.

The number of points to be added 16 is determined by the resolution 17 that is desired to obtain in the reconstruction process 13.

The value of such resolution 17 may be given either by conditions established by requirements 18 external to the reconstruction process 13 (for instance for observing with higher accuracy the object image) or for compensating the loss of resolution 19 due to the reconstruction process in applications requiring, in particular, the variation 20 of λ and/or d.

The number of points is not the only feature allowing a resolution improvement to be subsequently obtained.

In fact, it is needed to place the introduced fictitious points (i.e. the difference between the points computed as above and the acquired points) in a suitable way with respect to the detected points.

It is needed to be sure that the introduced zeros do not result in a transformed image (according to the function $\psi(l{\cdot}\Delta x,k{\cdot}\Delta y)$ described above) presenting false frequencies.

For example, placing zeros among not null values of a sinusoidal plot would clearly introduce frequencies far apart from the one of the sine.

Although single particular arrangements could be suitably adopted in specific cases, the preferred arrangement according to the invention is the one having the fictitious points as contour of the detected image, that is without interspersing them among the effective points.

Making reference to the example of figure 5, the fictitious points 50 are arranged symmetrically with respect to the contour of pixels 51 of the detected image.

This contour arrangement is proper to images in any number of dimensions.

The classical reconstruction process 13 is then applied to the expanded array of the hologram.

The expansion 15 of the array size of the hologram 12 allows obtaining, thanks to the DFT properties, a reconstructed image with a

lower spacing (that is with a better resolution) with respect to the reconstruction obtained without expanding the array.

In other words, the traditional reconstruction process based on the Fresnel transform implies a degradation of the resolution with which the object is reconstructed; instead, the addition according to the invention of new elements in the hologram array allows such resolution loss to be corrected at most obtaining a resolution equal to the physical one established by the sampling theorem.

In particular, if it is desired to obtain an image of the reconstructed object 14 with the same resolution of the digitized hologram 10, keeping constant wavelength λ and reconstruction distance d, it is necessary to expand the array of the hologram 12 from size $N \cdot M$ to size $(d\lambda/\Delta x^2)\cdot(d\lambda/\Delta y^2)$, as it is obtained by inverting formulas (1).

It would be theoretically possible to indefinitely improve the resolution of the holographic image by still adding new fictitious points. Actually, since the Fresnel transform re-distributes the intensity over all the points, beyond a certain number of fictitious points the intensity of many ones would be lowered below the background noise of the signal or the statistical noise of the same. However, it is matter of simple computation to determine the maximum number of fictitious points usable in any specific situation.

In figure 3 an example of application of the aforesaid method is reported. Such example is related to a coherent and monochromatic light source 1 with emission wavelength λ=532 nm, the observed object 3 is a Ronchi grating with step Λ=6.25 lines/mm, the acquisition and storing system is a CCD with N=512 and M=512 pixels and with square pixel size equal to $\Delta x = \Delta y$=6.7μm. A Ronchi grating illuminated with monochromatic light generates the known Talbot effect, i.e. by observing the light scattered by the grating at increasingly long distances the grating rows appear increasingly defocused, save at particular distances (multiple of the so-called Talbot distance, i.e. Λ^2/λ), where the rows appear well defined and focused again. Hence, by using such effect, we are allowed not to handle focusing problems.

In particular, the holographic reconstruction of a single line of the aforesaid grating, the hologram of which has been recorded at an effective distance of 170mm, is reported in figure 3a for several values of the distance d between hologram plane and observation plane.

The marks placed on the figure show the distances at which, due to Talbot effect, it is necessary to observe the grating rows well defined and focused.

The typical "trumpet" shape of figure 3a, obtained by varying distance *d*, is an indication of the reduction of the reconstruction pixel, according to equations (1).

The reduction of the reconstruction pixel, and hence of the reconstructed image resolution, under increasing distance *d*, prevents the grating rows to be sharply observed; hence, there is an information loss with the increase of the reconstruction distance.

The method according to the invention allows such information to be recovered.

The holographic reconstruction of the expanded hologram of the Ronchi grating is reported in figure 3b for the same values of distance *d* used in figure 3a.

In particular, hologram size has been increased by 512 points along both *x*–axis and *y*–axis, hence obtaining a hologram of 1024·1024 pixels. Obviously, the obtained shape is still a "trumpet" one, but it is possible to observe that by increasing the reconstruction distance it is still possible to determine distances at which the grating rows well defined and focused again. For better pointing out the advantage given by the present reconstruction method, a line is reported in figure 4a and figure 4b at a certain reconstruction distance (*d*=434 mm), related to figure 3a and figure 3b, respectively. The difference between such distance and the recording distance (170 mm) is multiple of the Talbot distance, and the grating rows should then appear well defined.

But observing figure 4a, it is noted that the loss of resolution does not allow the grating rows to be sharply distinguished.

The application of the method subject of the present invention allows overcoming such degradation. In fact, observing figure 4b, wherein the reconstruction of the grating expanded hologram has been carried out, it is noted that the grating rows are well visible and sharp.

The reconstruction method according to the invention represents a significant improvement with respect to the other methods present in literature. In fact, the method according to the invention acts on the object digitized hologram, and it may adapt the resolution of the object reconstructed image to the various requirements of multiple applications.

The invention is particularly, but not exclusively, intended for reconstruction processes in digital holography where there is the need to improve the resolution with which the complex field (amplitude and phase), transmitted or reflected or scattered by the object, is reconstructed, or to keep constant such resolution when the variation of other parameters, of which the same reconstruction is function, would tend to make the resolving power of the holographic technique worst. In numerous, above all metrological, applications, there exists the need to improve the resolution with which an object is observed, modifying as less as possible the observation apparatus and preventing the acquisition times from increasing. This last requirement is particularly felt in all those applications where a real time observation of the object is required.

The preferred embodiments have been above described and some modifications of this invention have been suggested, but it should be understood that those skilled in the art can make variations and changes, without so departing from the related scope of protection, as defined by the following claims

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IAP20 Rec'd PCT/PTO 25 JAN 2006

CLAIMS

1. Method for the reconstruction of holographic images, the holographic image being detected by an image detection device (9), the holographic image being transformed in a digitized hologram (10), the digitized hologram (10) being comprised of a number V_r of elementary pixels, the size of which being equal to the holographic image sampling intervals, and of the V_r values (51) respectively associated to the elementary pixels, the method comprising a first step (11,12) of processing the digitized hologram array, and a second step (13,15,16,17,18) of hologram reconstruction in the observation plane starting from the digitized hologram processed in the first step, **the method being characterised in that** the second step is carried out through discrete Fresnel Transform applied on an array of V_e values corresponding to pixels having size equal to that of said elementary pixels, wherein said array of V_e values (50, 51) includes said array of V_r values and an integer number $p = V_e - V_r > 0$ of constant values (50) equal to OS, said number V_e of values being inversely proportional to the desired pixel size to be obtained for the reconstructed image (14).

2. Method according to claim 1, characterised in that said p constant values (50) are null values $(OS = 0)$.

3. Method according to claim 1 or 2, characterised in that said p values (50) are arranged externally to said array of V_r values (51).

4. Method according to claim 3, characterised in that said p values (50) are arranged in a symmetrical way.

5. Method according to claim 3, characterised in that said p values (50) are arranged in a non-symmetrical way.

6. Method according to any one of the preceding claims, characterised in that the digitized hologram is a rectangular array of $V_r = N_r \cdot M_r$ values (51), each value corresponding to a rectangular pixel of sizes Δx, Δy.

7. Method according to claim 6, characterised in that the hologram reconstructed in the second step is represented by a rectangular array of $V_e = N_e \cdot M_e$ values, each value corresponding to a rectangular pixel of sizes $\Delta\xi = (\lambda d / N_e \Delta x)$ and $\Delta\eta = (\lambda d / M_e \Delta y)$, λ being the wavelength of the wave beam striking the object of which the hologram is recorded, and d the distance between the detection device and the object of which the

hologram is detected, $\Delta\xi$ and $\Delta\eta$ being the reconstructed holographic image sampling intervals.

8. Method according to claim 7, characterised in that $N_e = (\lambda d/\Delta x^2)$, $M_e = (\lambda d/\Delta y^2)$, $\Delta\xi = \Delta x$, $\Delta\eta = \Delta y$.

9. Method according to any one of the preceding claims, characterised in that, after the second step, if each holographic image sampling interval is not equal or less than a certain threshold, the number of values p (50) added to the digitized hologram array is increased and the second step is carried out again.

10. Method according to claim 9, characterised in that said threshold is a function of the signal-to-noise ratio of the holographic image.

11. Method according to any one of the preceding claims, characterised in that the method is performed for more than one holographic images detected at the same time for different wavelength λ, said more than one images being subsequently superposed in order to obtain a multi-colour final holographic image (14).

12. Computer program characterised in that it comprises code means apt to execute, when running on a computer, the method according to any one of claims 1 to 11.

13. Memory medium, readable by a computer, storing a program, characterised in that the program is the computer program according to claim 12.

14. Apparatus for detection of holographic images, comprising a digitized hologram processing unit, characterised in that the processing unit processes the detected data by using the method according to any one of claims 1 to 11.

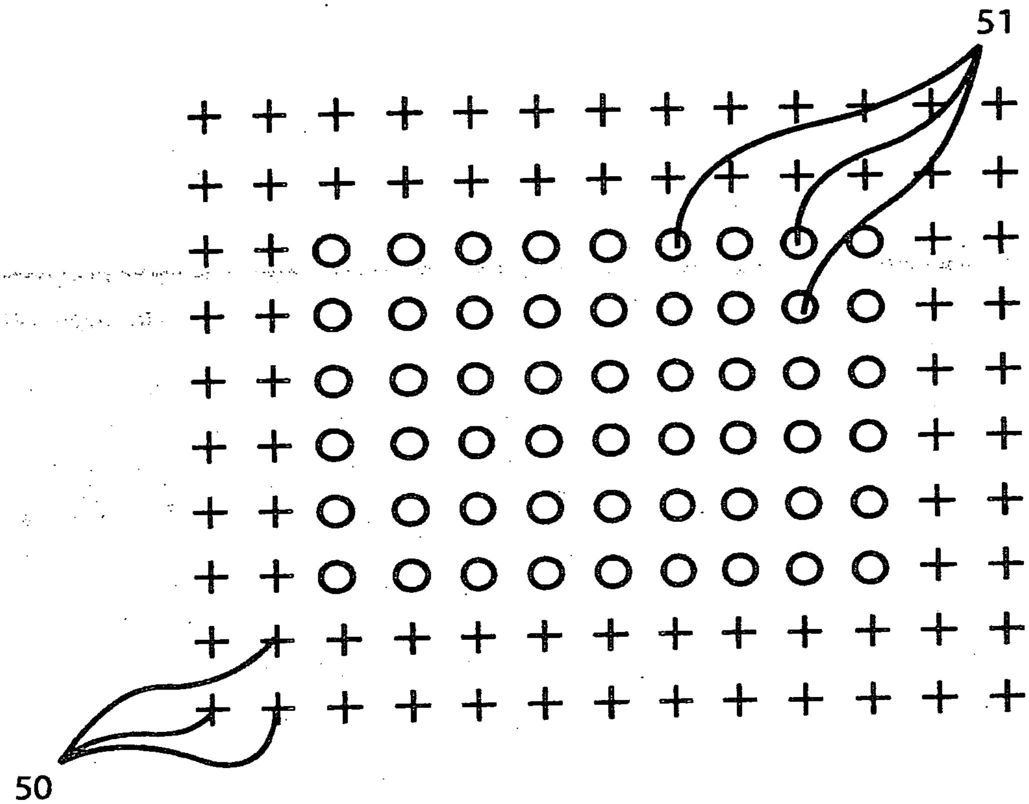

Fig. 5

VIC PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION CONCERNING SUBMISSION OR TRANSMITTAL OF PRIORITY DOCUMENT

(PCT Administrative Instructions, Section 411)

To:

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Date of mailing (day/month/year) 24 September 2004 (24.09.2004)	
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International publication date (day/month/year) Not yet published	Priority date (day/month/year) 13 August 2003 (13.08.2003)
Applicant CONSIGLIO NAZIONALE DELLE RICERCHE et al	

1. By means of this Form, which replaces any previously issued notification concerning submission or transmittal of priority documents, the applicant is hereby notified of the date of receipt by the International Bureau of the priority document(s) relating to all earlier application(s) whose priority is claimed. Unless otherwise indicated by the letters "NR", in the right-hand column or by an asterisk appearing next to a date of receipt, the priority document concerned was submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b).

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Priority date	Priority application No.	Country or regional Office or PCT receiving Office	Date of receipt of priority document
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